ECE445 Team 28
Design Document

Intelligent Square Stepping Exercise System for Cognitive-Motor Rehabilitation in Older Adults with Multiple Sclerosis

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1. Introduction

1.1 Problem

Persons with multiple sclerosis (MS) may experience declines in balance, mobility, strength, sensory, cognitive and mental health function. In 2019, almost a million people were diagnosed as MS (Nelson et al., 2019).

- Research shows that exercise training is associated with functional improvements in persons with MS (Sandroff et al., 2020). However, despite benefits, exercise participation remains low in persons with MS due to personal, environmental and societal barriers. Even though nowadays there are various devices for health people to monitor and aid their exercises, these devices may not be very suitable for people with MS. Therefore, there's a need to develop a system which specifically facilitates people with MS to do more physical exercise safely, thus helping them rehabilitate.

1.2 Solution

The proposed solution is a smart exercise mat designed to facilitate physical exercise for individuals with multiple sclerosis (MS), aiding in rehabilitation. The mat integrates both hardware and software components, providing real-time feedback to users on their movement patterns. It addresses common barriers to exercise for MS patients by ensuring safe, guided exercise experiences that can be performed at home. This system will help users track their progress and provide tailored feedback based on their specific needs.

The system will consist of a multi-layered sensing mat, as depicted in the image, where each square on the mat can detect and analyze the user's steps or movements. The mat will be synchronized with a software application that interprets the data, offering insights into the user's balance, coordination, and overall mobility. We will use Arduino as the microprocessor in early stages, but will replace it by a custom PCB in the final product. The hardware, embedded with sensors, will communicate wirelessly with the software, which will be customizable to the individual’s exercise regimen. The system is designed with at-home deployment in mind and could be refined through collaboration with an industry partner to ensure its robustness and user-friendliness.

1.3 Visual Aid

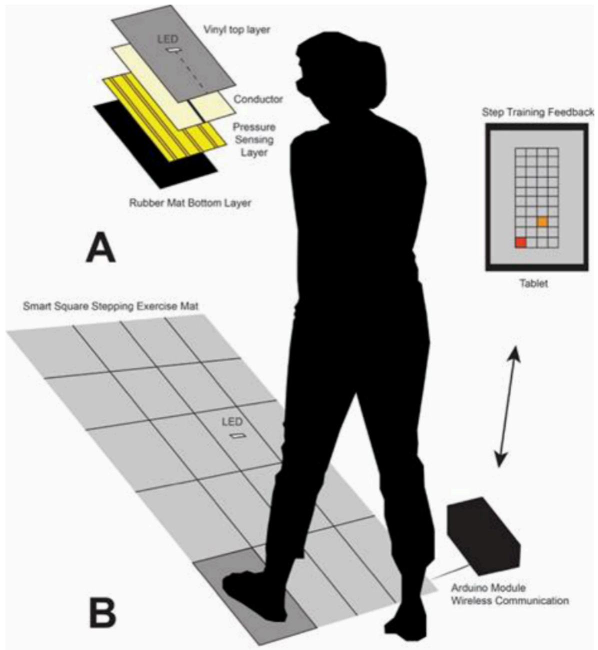

Figure 1. A) Cross-section of sensing mat, and B) Smart Square Stepping Exercise Mat (s-SSE) system.

Source: Adapted from Dr. Hernandez's pitched project presentation

1.4 High-level requirements

1. The mat must correctly detect stepping positions and time of users, with a minimum accuracy of 90%.
2. The system should provide feedback of the user's exercise within 10 seconds after each walk .
3. The mat should weigh less than 30kg and must be able to fold or roll.

2. Design

2.1 Physical Design

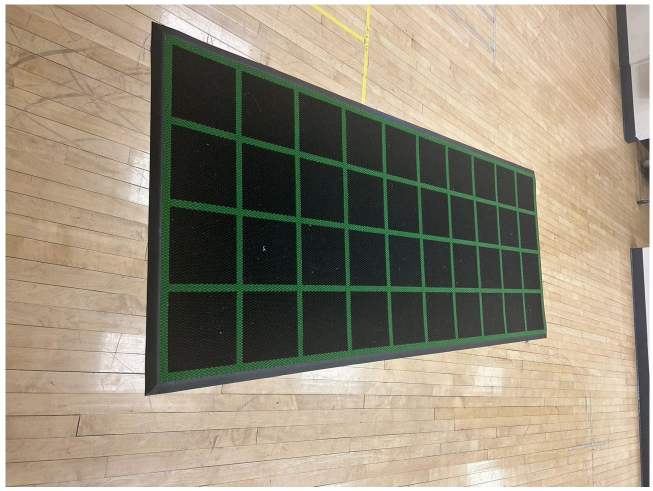

Fig.2 A training mat for MS patients

As shown in fig.2, the smart mat will look similar to this rehabilitation training mat for MS patients, with 4x10 square cells, each cell is about 25cm x 25cm. The surface of the mat will be made of SBR rubber, which is soft, flexible and non slippery.

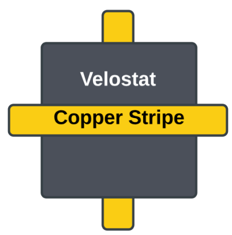

Fig.3 Structure of a sensor cell

Each cell will contain a custom pressure sensor, consisting of two layers of crossed copper stripes, with a velostat layer in between. The velostat is a pressure-sensitive conductive plastic material, its resistance decreases as pressure increases. In this way, we can monitor change in resistance to detect where the user is stepping at.

The copper stripes are then connected to the data processing unit (DPU). The DPU scans through all cells to gather the pressure data and send it to wireless devices.

2.2 Block Diagram

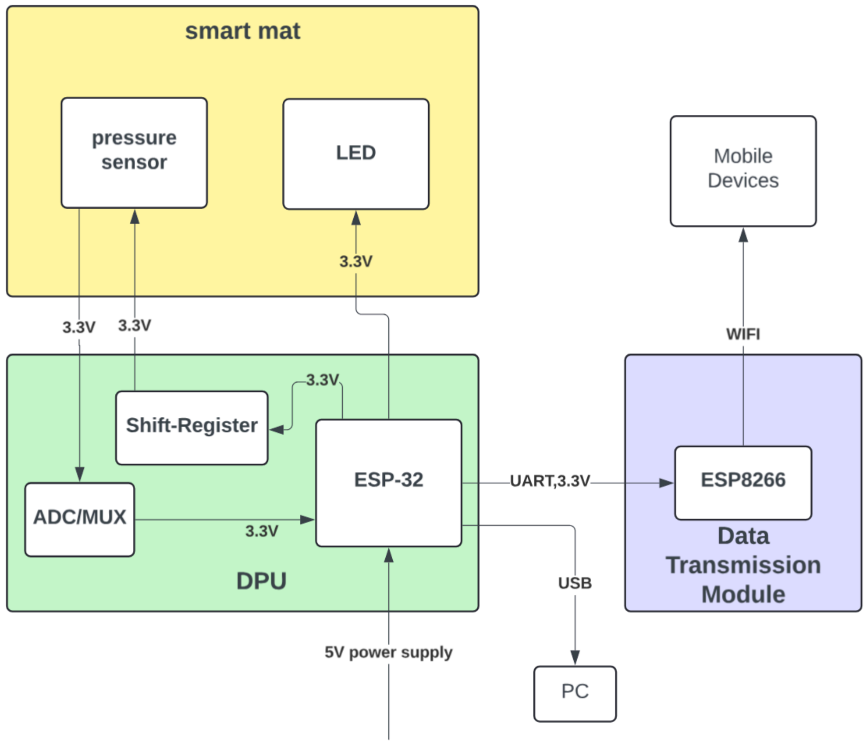

Fig.4 System block diagram

2.3 Functional Overview and Block Diagram Analysis

2.3.1 Smart Mat

The smart mat serves as the primary interface for users. It consists of multiple 25cm x 25cm squares, with LEDs attached to each of them. The user will step on these squares following the instructions given by the LEDs (and mobile apps) to step these squares in a given order. In this way, the user can get exercised to rehabilitate. There are customized low-cost pressure sensors beneath the mat, which will provide raw data to the data processing unit. During the revision, we found out that the dimension of the original design was a little small for the average users. To improve users' experience, we increased the length of each cell to 30cm, which should fit the length of adults' feet better. Also, due the increase in size and more detailed investigation in materials, we decide to increase the weight limit of the mat.

Requirements	Verifications
1. The mat must be easy to deploy and fold.	The mass of the mat should be less than 30kg. This can be verified using a balance. Also, the edges between each cell should be flexible.
2. While using the mat, the risk of current leakage must be minimized.	Use a multimeter to test over the surface of the mat while power is on. There shouldn't be a potential difference larger than 0.5V.
3. The mat must withstand intensive use.	Step on the mat, then fold it and then expand and repeat the process for 50 times. Then use a multimeter to measure the resistance/pressure behavior of randomly chosen cells, all the sensor cells should behave correctly.
4. The surface of the mat must be non-slip.	Ensure the mat is horizontally placed on the ground, use a slip meter to measure the coefficient of friction on either side of the mat. The coefficient of friction should be larger than 0.6.
5. The sensor must correctly reflect the position of stepping.	Place a mass more than 40kg on a random cell, use a multimeter to measure the change in resistance across the corresponding copper stripe pairs.

2.3.2 Data Processing Unit

This subsystem consists of a microprocessor, its peripherals, several multiplexores and shift-registers. Since we have to monitor 40 sensor cells using the limited pins of the microprocessor, we introduced a scanning method. We use the shift register to circle through all cells row by row, setting a copper stripe to high voltage each time. At the same time, we use a multiplexor to scan the cells column by column to monitor the output voltage. In this way, we can detect the time and location of a cell and when it was stepped on. The scan frequency is set to 8 HZ to reduce the number of samples to an appropriate amount, but this frequency is still high enough compared to humans' walking frequency. This unit also manages the communication with the data transmission module to send the analyzed data to connected devices. The accuracy and responsiveness of the data processing unit are essential for providing timely feedback to users.

The DPU should run on at most 5V, which means it can be easily powered by a conventional USB wire with a power adapter.

The simplified schematic shows how we manage to control 40 cells with limited pins on the chip. The microcontroller gives serial input to the shift registers with a 1 and multiple 0s. This signal is then passed in several shift registers in series. Each parallel output pin is connected to a copper stripe through a diode. In this way, the cells are set to active in sequence. When each cell is active, the mux will scan through all the output pins of the cells. In this way , we can determine which cell is stepped on at each scanning cycle.

During the revision and experiments, we had a more detailed design regarding the power system. The LED strips use 12V DC input, we will use a 12V DC power supply, and use a 12V-to-5V step down transformer to power the control unit and other devices.

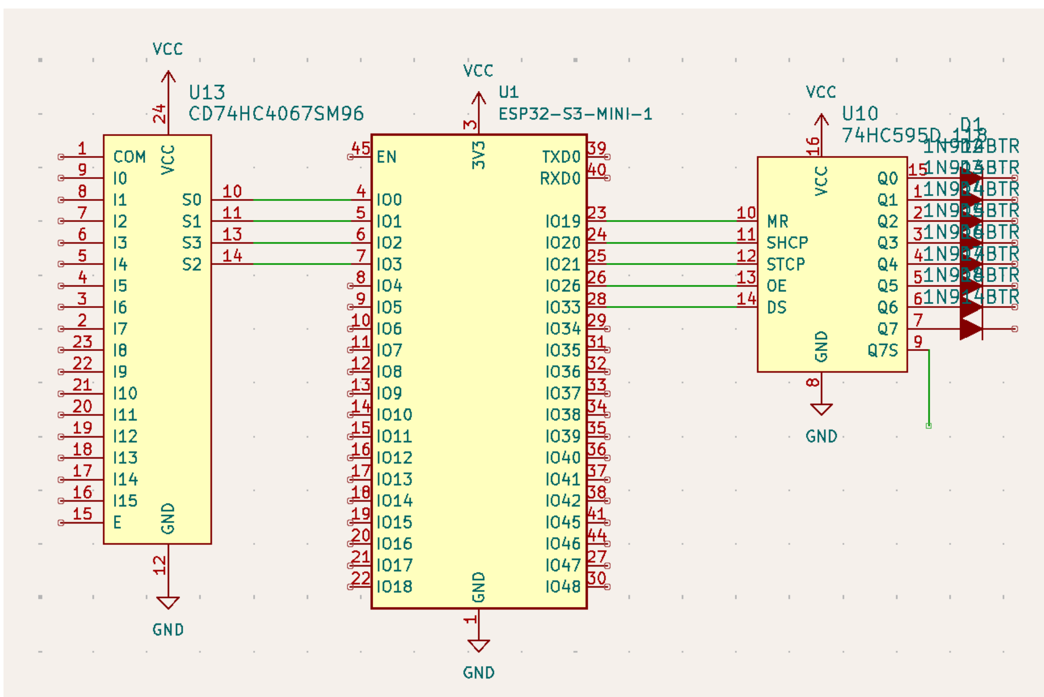

Fig.5 DPU schematic

Requirements	Verifications
1. The DPU should have overload protection in case the user connected a wrong power source.	Implement a fuse in the circuit and test with early prototypes.
2. The DPU should synchronize the Shift-registers and multiplexores to correctly label times and positions of stepping.	Turn on the mat and let someone step on the cells in a given order. Compare the recorded stepping sequence with the actual sequence. If they matches, the mat is functioning correctly.
3. The DPU’s heating must be controlled to an acceptable level.	Using a infrared temperature sensor, the external cover of the DPU should not exceed 40 degrees Celsius, and the chip’s temperature should not exceed 90 degrees Celsius.
4. The time delay for processing the data and sending it to mobile devices should not exceed 5s.	Start timing while start walking on the mat, check if the mobile device interface received the input within 5s.

2.3.3 Data Transmission Unit

The Data Transmission Unit is responsible for sending the processed data from the Data Processing Unit to external devices, such as a mobile app or computer, for user feedback and analysis. This subsystem will use wireless communication technology to transmit real-time information about the user's movements on the mat, allowing them to receive instant feedback on their performance and progress. For our design, we will use Wi-Fi or Bluetooth communication protocols, depending on the target platform and distance requirements. The ESP8266 SoC, which has built-in Wi-Fi and Bluetooth capabilities, will handle the data transmission. During revision, we decided to use ESP32-S2-mini1/1U as the microprocessor. Since they have 2.4GHz wireless transmission ability, we don’t need an external DPU.

Requirements	Verifications
1. The data transmission must occur wirelessly and reliably without noticeable lag (with a transmission latency of less than 1 second).	Ensure the transmission latency between the mat and the connected device is less than 1 second. This can be verified by logging timestamps at the source and destination points and comparing them.
2. The system must be able to connect to at least one mobile device and transmit data without interference or signal loss over a range of 10 meters.	Test the range of the wireless transmission by placing the mobile device at different distances (from 1m to 10m) and ensuring consistent data reception without disconnections (over 99 percent of data should be received in the correct time sequence).
3. The data sent from the mat to the mobile device should include time, location, and pressure data for each step.	Verify that all required data points (time, location, pressure) are correctly received on the mobile device. Conduct multiple tests by walking across different areas of the mat and confirm the data matches the expected results.

2.3.4 Software subsystem

The software is used as a user interface on mobile devices. Which can let users select exercise plans and give feedback to users.
Since this is a pitched project, other group members outside of this class will work on the software for remote devices, including the user interface. We will not put too much effort into this part, while making sure it matches well with the hardware and firmware. Here’s a flow chart of the current software design from the software group.

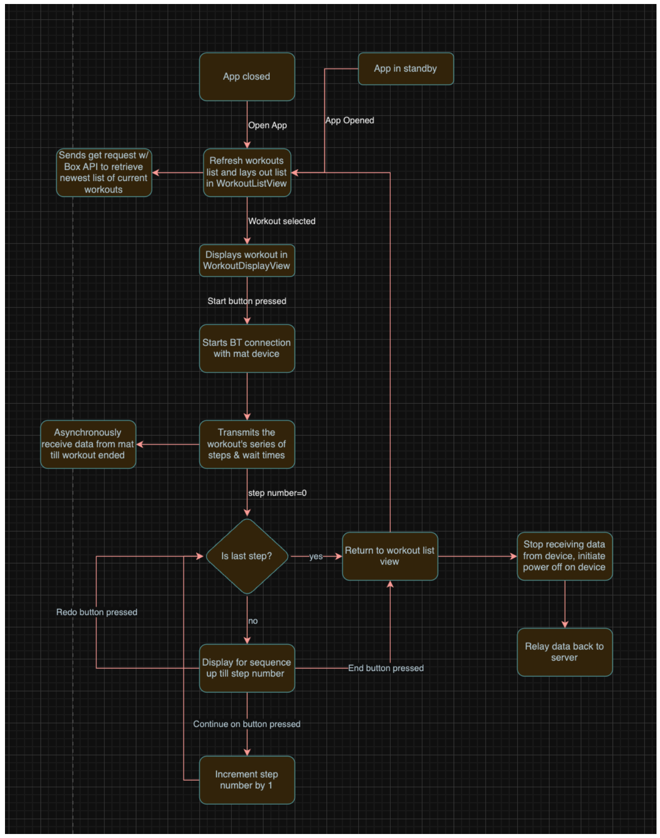

Fig.6 Flow chart of software

2.4 Tolerance Analysis

- **Risk Aspect:** In the smart mat design, a critical aspect is ensuring accurate detection of foot placement on the mat's individual blocks. A potential error arises when the user steps near the edge of a block, leading to a false positive (misinterpreting the step as on the block when it should be detected as not on the block).
- **Sensor Configuration:** Each block has three vertical copper strips with a layer of piezoelectric material underneath. Below the piezoelectric layer, there are three horizontally arranged copper strips, forming nine intersection points. When a foot presses down on any of these intersections, the resistance of the piezoelectric layer at the intersections decreases, copper strips above and below the piezoelectric material connect and conduct electricity.
- **Geometrical Definitions:**
    - Block area (B): Let the area of each block be a square, with side length s, so $B = s^2$

- Detection area (D): The area enclosed by the nine intersections formed by the copper strips.

  The intersection points form a grid within the block.

  Let the side length of the detection area be d, so $D = d^2$.

  d must be smaller than s to prevent false positives near the edges of the block.

- **Valid Step Condition:**
  - A step is considered valid if the foot's pressure falls entirely within the detection area D.
  - The foot should activate one or more of the intersections inside D.
- **Error Definition:**
  - False positive: When a step near the block's edge is detected as being inside the detection area.
  - This happens when the foot overlaps the boundary of D but does not fully land inside D.
- **Mathematical Model for Tolerance:** To minimize edge errors, we can define a tolerance factor, t, representing the margin between the detection area and the block's edges.
  - Step Validity Condition: The detection area must be centered within the block with a margin to the edges.
  - The foot should land in an effective detection zone that excludes a buffer region of width t along the edges of the block.
  - This gives: $t = (s - d)/2$
- **Design Constraints:**
  - The detection area should be sufficiently smaller than the block area to avoid errors: D < B
  - You can adjust t based on the desired sensitivity and precision of detection to minimize false positives. A larger t reduces the chance of errors near the edge but decreases the detection zone.
- **Risk Analysis:**
  - A large margin t reduces the false positives but may lead to missed steps if the foot falls near the boundary.
  - Too small t increases the chance of false positives, as pressure on the block's edge might trigger the intersections.

2.5 Cost Analysis

- **Overhead: $11250 + $405 = $11655**
  - **Labor: $45/hr * 2.5 hr/day * 50 days * 2 persons = $11250**
  - **Rent: $135/month*3 = $405**
- **Parts: $831.95 * 1.15(shipping costs and taxes) = $400.15**

Description	Manufacturer	Part #	Link	Quantity	Cost (per unit)	**Total Cost**
Wi-Fi Microcontroller SoC	Espressif Systems	ESP32-S2-MINI-1-N4	https://www.digikey.com/en/products/detail/espressif-systems/ESP32-S2-MINI-1-N4/13180194	1	$2.00	$2.00
Shift Register	Nexperia USA Inc.	74HC595D,118	https://www.digikey.com/en/products/detail/nexperia-usa-inc/74HC595D-118/763087	1	$0.30	$0.30
Custom PCB (final product)	PCBWay	-	https://www.pcbway.com/?adwgc=666&campaignid=172480651&adgroupid=8787904531&feeditemid=&targetid=kwd-297443275619&loc_physical_ms=9022185&matchtype=p&network=g&device=c&devicemodel=&creative=347469560617&keyword=pcbway&placement=&target=&adposition=&gad_source=1&gclid=Cj0KCQiAire5BhCNARIsAM53K1jUuNY4ic5qOwnBCbalwJuchOzylJH3VutH4T1yP91xMhWmKAxwI48aAkW5EALw_wcB	2	0	0
SBR Rubber Mat	Rubber-Cal	03-167-W-25	https://www.homedepot.com/p/VEVOR-Black-10-x-6-x-0-28-60-sq-ft-Gym-Flooring-Mat-60-Rubber-Non-Slip-High-Density-Yoga-Mat-Fitness-with-Bag-Carry-DXYJD6YC10YCV2K3FV0/331497295	1	$124.00	$124.00

Pressure Sensors (Velostat)	Adafruit Industries	1361	https://www.digikey.com/en/products/detail/adafruit-industries-llc/1361/7241456?utm_adgroup=&utm_source=google&utm_medium=cpc&utm_campaign=PMax%20Shopping_Product_Medium%20ROAS%20Categories&utm_term=&utm_content=&utm_id=go_cmp-20223376311_adg-_ad-__dev-c_ext-_prd-7241456_sig-Cj0KCQiAire5BhCNARIsAM53K1iyLk1hwmlEIreC6UVQbo9Lh6y4NDrjqArPjcr6LsOj15B27E3dMbYaAjWBEALw_wcB&gad_source=1&gclid=Cj0KCQiAire5BhCNARIsAM53K1iyLk1hwmlEIreC6UVQbo9Lh6y4NDrjqArPjcr6LsOj15B27E3dMbYaAjWBEALw_wcB	5	$4.95	$24.75
Copper Strips	VDS	Vaincre Copper Tape (1inch X 66 FT), Copper Foil Tape for Stained Glass, Copper Tape for Slugs Conductive Adhesive, Copper Flashing Conductive Tape for Guitar, EMI Shielding	https://us.amazon.com/Vaincre-Conductive-Adhesive-Flashing-Shielding/dp/B0C1442K27/ref=sr_1_6?crid=13R49V5U9W5VV&dib=eyJ2IjoiMSJ9.s04BWgdU4cB1O0KhUtx5ahb4DF15M7kQ42x5O3bje28HO6RWogqzc6gxgCmcbVuORXLM8tKqaA7VnMTfO4sq2_FuCaKfRLfgHwvfQft6Y4aYR5_ZNxpNFZ3Yn4WzYYLXDY79TNcbAJXvJFliInDqZY_O8hZd7qg_fDio3BmI4ACnqIHK35DxCat4bP6pwxz2v9HYRronyfkF1frUntGTM1DKu9KG_4wxQikCrtqPSrN1YTNHnxN6qsSQpUrXUpPOrTNUsnKeUVEwReZN0kSOpRyVux2H1Gc9XfZdloOnsc	2 rolls	$6.59	$13.18

			s.RbtR4qfzBhVKdQ5PashNebcnKBDxcwziLxvH5gOI2ls&dib_tag=se&keywords=copper+stripes&qid=1727821582&s=industrial&sprefix=copper+stripes%2Cindustrial%2C132&sr=1-6			
Wireless Module (Bluetooth)	Espressif Systems	ESP32-WROOM-32E-N4	https://www.digikey.com/en/products/detail/espressif-systems/ESP32-WROOM-32E-N4/11613125	1	$2.5	$2.5
LED Strip (for feedback)	BTF-LIGHTING	BTF-LIGHTING WS2815 (Upgraded WS2812B) 16.4ft 150 Pixels Magic Dream Color Individually Addressable RGB LED Flexible Strip Light 5050 SMD Dual Signal IP30 Non-Waterproof DC12V Black PCB	https://www.amazon.com/BTF-LIGHTING-Upgraded-Individually-Addressable-Non-Waterproof/dp/B07LG5S6DK/ref=sr_1_1?crid=19KVCRDSAT4UH&dib=eyJ2IjoiMSJ9.IV8hmhHk3S-uCgHrFfaHlYJ0EW7grIL3H7Hc-6n1AQo7iQZoYbqlbiF_uX2AthvmN4XklPSHcLnn2VArEC51k90ZK2xNzPFtA5TG36fW_gf2RP369W62X2l-TDDfaVEaHHTYY8bDXHS-GFzCHaoQ3x-S5eP12c34NgmbchEgH8ykVrNfNKDVC8Cl8WlOoeFuaCidXxLSNzw56eMYl1pWN6_bl39pJT8Y11lZNyliNYchB55f55cjAAm6ampd319BH5oLQT1Y50YhOpUlMypW-uzc8ShEw8Ev5-fQVp6r--g.9fsF9HT_9ZsBaoqCN-kEziEqRK37O2lI3q0egilXoV8&dib_tag=se&keywords=ws2815%2B6.6ft&qid=1730328048&s=hi&sprefix=ws2815%2B6.6ft%2Ctools%2C71&sr=1-1&th=1	6	$26.99	$161.94
Power Supply	Mean Well	GST25A12-P1J	https://www.digikey.com/en/products/detail/mean-well-usa-inc/GST	1	$13.70	$13.70

			25A12-P1J/7703648			
Enclosure for Electronics	Hammond	1591XXCFLBK	https://www.digikey.com/en/products/detail/hammond-manufacturing/1591XXCFLBK/2357858	1	$8.78	$8.78
Insulation Material	Surface Shields	24 in. x 50 ft. Carpet Protection Self Adhesive Film	https://www.homedepot.com/pep/SURFACE-SHIELDS-24-in-x-50-ft-Carpet-Protection-Self-Adhesive-Film-CS2450/205187255?mtc=SHOPPING-BF-CDP-BNG-D23F-023_014_FLOOR_TOOLS-NA-NA-NA-PLALIA-NA-NA-NA-NA-NBR-NA-NA-NEW-2024&cm_mmc=SHOPPING-BF-CDP-BNG-D23F-023_014_FLOOR_TOOLS-NA-NA-NA-PLALIA-NA-NA-NA-NA-NBR-NA-NA-NEW-2024-71700000118086450-58700008689999345-9270007981067149 0&gclid=9781c9e2a90119041ea8aec329504ded&gclsrc=3p.ds&msclkid=9781c9e2a90119041ea8aec329504ded	1 roll	$22.00	$22.00
Non-slippery Film	Dycem	50-1502BLK Non-Slip Material Roll, Black, 8" X 3.25 ft	https://www.amazon.com/Dycem-Non-Slip-Material-Roll-Blue/dp/B002WQ7AB2/ref=asc_df_B000C23XJG?tag=bingshoppinga-20&linkCode=df0&hvadid=80814156492517&hvnetw=o&hvqmt=e&hvbmt=be&hvdev=c&hvlocint=&hvlocphy=&hvtargid=pla-4584413735346580&th=1	1 roll	$27.00	$27.00

- **Total: $12055.15**

2.6 Schedule

Week	Task	Person
September 30th - October 6th	Single Cell Prototype Test	Junmin & Hank
October 7th - October 13th	PCB/Schematic Design	Hank
October 14th - October 20th	Half-size Prototype	Junmin
October 21st - October 27th	LED Schematic	Junmin
October 28th - November 3rd	LED Prototype	Junmin
November 4th - November 10th	Full-size Prototype	Junmin
November 11th - November 17th	Test and Debug	Junmin & Hank
November 18th - November 24th	Mock Demo	Junmin & Hank
November 25th - December 1st	Final Test	Junmin & Hank
December 2rd - December 8th	Final Demo	Junmin & Hank
	Mock Presentation	Junmin & Hank
December 9th - December 15th	Final Presentation	Junmin & Hank

3. Ethics and Safety

- **Ethical Issues**
    1. User Privacy and Data Security: Collecting user data for feedback and monitoring raises concerns about privacy and security. According to the IEEE Code of Ethics, engineers must ensure the privacy of individuals and protect sensitive data (IEEE, 2020). To mitigate this, we will implement robust data encryption, anonymization techniques, and ensure compliance with data protection regulations like GDPR or HIPAA. User consent will be obtained for data collection, clearly outlining how the data will be used.
    2. Accessibility: Ensuring that the smart mat is accessible to individuals with varying degrees of mobility and cognitive function is crucial. The ACM Code emphasizes the importance of considering diverse user needs in technology design (ACM, 2018). We will involve users with MS in the design process to ensure usability and effectiveness across different levels of capability.
    3. Misuse of Technology: There is a risk of the mat being misused, intentionally or unintentionally, leading to injuries or ineffective rehabilitation. The IEEE Code advises that engineers should avoid harm to others (IEEE, 2020). To address this, we will provide comprehensive instructions and guidelines for safe use, along with safety warnings in the user manual.

- **Safety Concerns**
    1. Physical Safety: Users may be at risk of falling while exercising on the mat. To minimize this risk, we will ensure the mat has a non-slip surface and is lightweight enough to be easily repositioned for safe use. Additionally, we will conduct user testing to identify potential hazards during exercise.
    2. Electrical Safety: The integration of electronic components poses risks related to electrical safety. We will ensure that all components are properly insulated and that the mat is water-resistant to prevent short-circuits.
    3. Data Security: With sensitive health data being transmitted, it is essential to follow cybersecurity standards such as the NIST Cybersecurity Framework (NIST, 2024). We will incorporate security protocols to protect against unauthorized access and data breaches.

Reference

[1] Association for Computing Machinery, “ACM Code of Ethics and Professional Conduct,” *Association for Computing Machinery*, Jun. 22, 2018. https://www.acm.org/code-of-ethics

[2] B. M. Sandroff, C. D. Jones, J. F. Baird, and R. W. Motl, “Systematic review on exercise training as a neuroplasticity-inducing behavior in multiple sclerosis,” *Neurorehabilitation and Neural Repair*, vol. 34, no. 7, pp. 575–588, May 2020. doi:10.1177/1545968320921836

[3] E. Sebastião *et al.*, “Home-based, square-stepping exercise program among older adults with multiple sclerosis: Results of a feasibility randomized controlled study,” *Contemporary Clinical Trials*, vol. 73, pp. 136–144, Oct. 2018. doi:10.1016/j.cct.2018.09.008

[4] IEEE, “IEEE Code of Ethics,” *ieee.org*, Jun. 2020. https://www.ieee.org/about/corporate/governance/p7-8.html

[5] L. M. Nelson *et al.*, “A new way to estimate neurologic disease prevalence in the United States,” *Neurology*, vol. 92, no. 10, pp. 469–480, Mar. 2019. doi:10.1212/wnl.0000000000007044

[6] NIST, “Cybersecurity Framework,” *National Institute of Standards and Technology*, 2024. https://www.nist.gov/cyberframework